

Power Considerations for an Early Manned Mars Mission Utilizing the Space Station

(NASA-TM-101436) POWER CONSIDERATIONS FOR
AN EARLY MANNED MARS MISSION UTILIZING THE
SPACE STATION (NASA) 15 p CSCL 10B

N89-13492

Unclass

G3/20 0179843

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Prepared for
Case for Mars III
cosponsored by the American Astronautical Society, Jet Propulsion
Laboratory, Los Alamos National Laboratory, Ames Research
Center, Lyndon B. Johnson Space Center, George C. Marshall
Space Flight Center, and The Planetary Society
Boulder, Colorado, July 18-22, 1987



POWER CONSIDERATIONS FOR AN EARLY MANNED MARS MISSION
UTILIZING THE SPACE STATION

Martin E. Valgora*

Power requirements and candidate electrical power sources were examined for the supporting space infrastructure for an early (2004) manned Mars mission. This two-year mission (60-day stay time) assumed a single six crew piloted vehicle with a Mars lander for four of the crew. The transportation vehicle was assumed to be a hydrogen/oxygen propulsion design with or without large aerobrakes and assembled and checked out on the LEO Space Station. The long transit time necessitated artificial gravity of the crew by rotating the crew compartments. This rotation complicates power source selection. Candidate power sources were examined for the Lander, Mars Orbiter, supporting Space Station, co-orbiting Propellant Storage Depot, and, alternatively, a co-orbiting Propellant Generation (water electrolysis) Depot. Candidates considered were photovoltaics with regenerative fuel cells or batteries, solar dynamics, isotope dynamics, and nuclear power.

BACKGROUND

Interest in travel to the planet Mars has received dramatically increased interest since the National Commission on Space Report, "Pioneering the Space Frontier," was published in May 1986. NASA responded to this independent recommendation by undertaking a series of feasibility studies examining a variety of approaches to manned visits to Mars. This author was involved in two feasibility studies

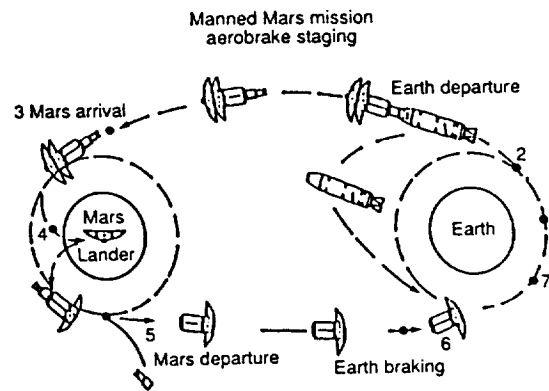
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supported by representatives from NASA Headquarters and the NASA field centers. One study was led by the Langley Research Center¹ in January 1987 to examine the impact of an early manned Mars mission on the planned Space Station and its associated infrastructure. The NASA Lewis Research Center was assigned responsibility in power concepts and impacts. This included considerations of the required technology development activities that could take place on the Space Station infrastructure. Therefore, the technology options for the mission must be known in some depth by performing feasibility analyses on a strawman mission. The second study was led by the Marshall Space Flight Center² and focused on the feasibility and impacts of using a tether to rotate several separable sections of the Mars space vehicle to create artificial gravity for these relatively long voyages to Mars. Artificial gravity is needed mainly for the most important consideration for this mission, which is the safety and health of the crew. Again, the NASA Lewis was assigned responsibility in power concepts and impacts. In general, the Langley study found that the Space Station was a good, versatile platform for developmental tests and assembly of the Mars space vehicle; however, some currently planned Space Station activities may have to be shifted to other platforms. The Marshall study found that use of tethers for artificial-G was definitely feasible and desirable and would only drive up the mass by about 25 percent over a zero-G vehicle, but would still require zero-G countermeasures since zero-G would be a possible abort mode. The results of the power system portions of these feasibility studies are blended together and presented in this paper in concise, top level summary statements.

MISSION PHASES

Figure 1 illustrates the various mission phases using a single vehicle. Phase 1 is assembly and checkout in low-Earth orbit and is further illustrated in Fig. 2. Also included in this phase is the fueling of the vehicle at the propellant depot, final checkout, and launch. Phase 2, after first stage separation, includes orbit corrections and deployment of the habitat modules for spin-up for artificial gravity. Phase 3 requires habitat spin-down and retraction behind the aerobrake, entry and braking in the Mars atmosphere and orbit raising and circularization. Phase 4 includes aerobrake descent to the Mars surface by the lander, surface operations of one to two months, and then ascent and rendezvous with the orbiter. Phase 5 includes second stage engine firing for Mars departure, engine separation, and deployment and spin-up of the habitat modules for artificial gravity. Phase 6 includes habitat spin-down and retraction behind the aerobrake, entry and braking in Earth atmosphere, and then orbit raising and circularization. The last phase is rendezvous and docking with the Space Station.

The space infrastructure elements required for this mission that need significant power are the Space Station and the nearby Propellant Depot in low-Earth orbit, and the Mars space vehicle consisting of the Mission Module (Orbiter) and the Mars Excursion Module (Lander).



MISSION PHASE

1. Assembly and checkout in LEO
2. LEO departure
3. Mars capture
4. Mars operations
 - Descent
 - Surface operations
 - Ascent
5. Mars departure
6. Earth capture
7. Space Station rendezvous and docking

Figure 1. - Manned Mars mission profile.

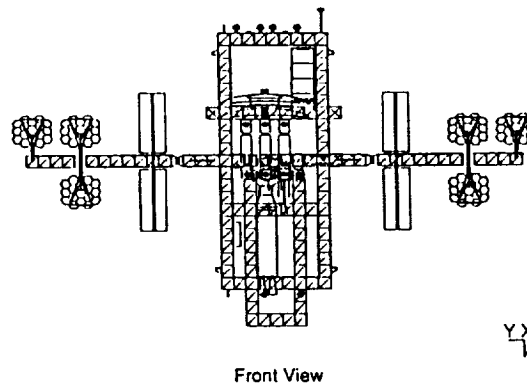


Figure 2. - Completed manned mars space vehicle attached to the space station.

SPACE STATION

The planned Space Station power requirement will start at about 75 kW for the early years and grow to somewhere between 150 and 300 kW, depending on how ambitious we are in combining non-Mars activities concurrently with the Mars mission activities.

The Space Station power system is very versatile with high growth capability and is considered to readily accommodate this mission. If necessary, the growth plan of replication by adding pairs of 25 kWe solar dynamic modules or additional photovoltaic panels can be accelerated to meet this requirement. Figure 2 illustrates a growth version of the Space Station with the completed aerobreak version of the Mars vehicle

fully assembled: It is important to note that this Mars mission dominates the Station for years--even prior to vehicle assembly because of precursor activities in life science and hardware development.

PROPELLANT DEPOT

Propellant Storage Depot Option

A large propellant storage depot is required to store the liquid hydrogen and oxygen propellant for the Mars vehicle at a safe distance from the permanently manned elements. Figure 3 illustrates a possible configuration for this depot.

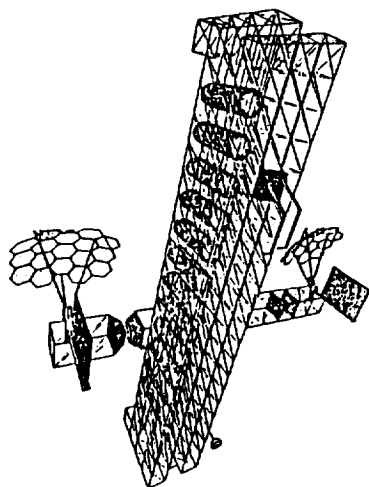


Figure 3. - Propellant tank farm concept.

This facility would require power to refrigerate and transfer liquid H_2 and O_2 . Standard Space Station power modules would be the most cost effective way to satisfy this power need. Balanced pairs of photovoltaic arrays with NiH_2 batteries or balanced pairs of solar dynamic modules (illustrated in Fig. 3) are mounted similar to the Space Station configuration.

Propellant Generation (Water Electrolysis)/Storage Depot Option

A possible option would be to launch and store water and then to electrolyze water at a rate dictated by the propellant requirements and schedule. If water launch and storage is considered beneficial, then power for electrolysis, liquefaction, and propellant handling could be satisfied by several SP-100-type nuclear reactors with advanced dynamic conversion systems. It was estimated that the power level required to keep up with the propellant launch rate for the Mars mission alone would be in the megawatt region. It is considered that the SP-100 reactor could be ready in this time period, and, therefore, should be further examined for this application.

MARS SPACE VEHICLE

Figure 4 illustrates an aerobrake concept of the Mars Space Vehicle with liquid oxygen-liquid hydrogen propulsion stages, habitat modules, logistics module, Mars excursion module (lander), and large aerobrakes

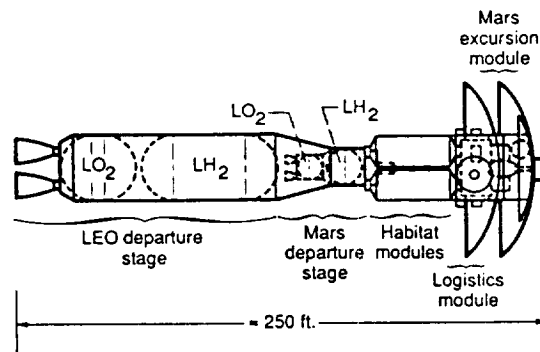


Figure 4. - Mars space vehicle.

for Mars entry and Earth entry and a small aerobrake for lander descent. Not shown is a mechanism for deployment (separation) of the habitat modules that can then be rotated to create artificial gravity for the crew in order to assure good health throughout the long journey of typically one to two years round trip. This mechanism could be a rigid deployable/retractable boom to extend the habitats and provide a radius of rotation, or it could be a reliable tether system to separate the vehicle into two or more bodies rotating about their combined center of gravity, which was examined in Ref. 2. Spin-up and spin-down would be accomplished by a low thrust propulsion system. For safety and maintenance purposes, it is very desirable to locate the electrical power system at the habitats.

The following discussion on power for the Mars Space Vehicle will deal first with the Mission Module (Orbiter) and then with the Mars Excursion Module (Lander).

Mission Module

The total power requirements were estimated to be about 25 kWe. Approximately one half of this would be used by the ECLSS for the crew of six, and the other half used for mission operations and experiments. The Mission Module power requirement could be satisfied with multiples of power modules (2 of 12 kWe, 4 of 6 kWe, etc.) for redundancy and possible commonality with the Mars Excursion Module (Lander) power system. For solar power systems with energy storage, an elliptical Mars orbit was assumed with a 4-hr (worst case) shadow and 20 hr of sunlight. Solar power modules that require deployment and pointing would be complicated by any Mission Module rotation (for artificial gravity) and forces caused by thruster firing and aerobraking which necessitates multiple retractions and redeployments.

Normal Operation

Power technology candidates that were considered for normal operation are: photovoltaic systems with energy storage consisting of advanced batteries or regenerative fuel cells; small nuclear reactor of the SP-100 type; isotope dynamic power system; hydrogen-oxygen fuel cells capable of using propellant grade fuel; and a solar dynamic power system. The technology level assumed is that of the Space Station era, and is rather conservative with moderate technology funding. More aggressive funding in selected technology areas could result in sizeable mass reductions.

1. Photovoltaic Systems with Energy Storage

Photovoltaic blankets could be either body mounted or mounted on deployable/retractable arrays. Body mounted blankets would be lightweight, rugged, and not require pointing, but would be limited by available body area. Deployable/retractable arrays would be heavier, more delicate, and would have to have very reliable deployment/retraction systems.

A likely flight condition to conserve propellant mass is to locate the vehicle spin axis at a right angle to the ecliptic plane. This would cause solar arrays that are not despun to rotate with respect to the sun. This condition would require solar cells on both sides of the array and additional cells to compensate for cosine losses. Therefore, this flight condition requires about four times the solar cells as a sun-pointing array and results in about a 100 percent mass increase. An attractive candidate for this spinning condition is a roll-out blanket with very lightweight cells on both sides, such as amorphous silicon that can reduce the mass by about 70 to 80 percent compared to conventional foldup approaches. Solar arrays could also be despun at the vehicle center of gravity in order to minimize the mass penalty due to artificial gravity forces. This option, however, would place the arrays at a considerable distance from the habitats which was considered undesirable and would complicate the vehicle retraction mechanism with heavy power lines.

Energy storage could be advanced batteries such as lithium or sodium-sulfur or regenerative fuel cells that can also use H₂O boiloff and excess H₂O propellant. Regenerative fuel cells can also be integrated with the ECLSS for mass saving.

Preliminary calculations indicate a system with advanced photovoltaics and energy storage is a strong candidate and could weigh 1000 kg per 12 kWe module, which is consistent with current technology program plans. More aggressive technology programs could reduce the mass considerably.

2. Isotope/Dynamic Systems (Brayton, Rankine, or Stirling)

Isotope power systems are independent of pointing and location constraints. However, isotopes are in limited supply and availability is not assured. Advanced planning and investment could yield 10's of kWe output. A high efficiency dynamic converter is considered necessary to minimize the isotope requirement. Isotope systems have higher active heat rejection than PV systems and, therefore, larger radiators with space viewing area preferably away from the sun. Isotope systems also have a safety issue in the case of a launch failure on Earth re-entry. System mass could be about 1500 kg per 12 kWe module which makes it attractive.

3. Fuel Cell Systems (Not Regenerative)

Hydrogen-oxygen fuel cells can use the propellant boiloff and excess propellant and can be integrated with the ECLSS. Hardware weights are relatively light, perhaps 500 kg per 12 kWe. But the mass of fuel is prohibitive, about 180 000 kg for 25 kWe over a 700 day mission. However, use of fuel cells for emergency power must be examined for the case of an emergency that results in a mass abort flyby. This case would free up considerable second stage H-O propellant for use in a fuel cell.

4. Solar Dynamic System

The solar dynamic system is complicated by pointing and deployment/retraction similar to the photovoltaic system. However, the solar dynamic system has a much tighter pointing requirement and would need to be located on a despun section of the vehicle at a considerable distance from the habitats.

Extrapolation of Space Station technology indicates a mass of about 4000 kg per 12 kWe module which is considered heavy for the mass sensitive Mars mission.

5. Nuclear Reactor/Thermoelectric Converter

Nuclear reactors are free from the pointing requirement of a solar power system. But, in order to minimize the very high mass of a man-rated shield, reactors are commonly mounted on a long boom with reduced shielding. For this mission as currently conceived using aerobrakes, there are configuration difficulties in locating the reactor boom, crew and lander with respect to the aerobrakes. Nuclear systems located on long booms can be lightweight--perhaps as low as 2000 kg, depending on configuration, for 25 kWe output with a man-rated shield and a long boom. However, once a reactor is energized and becomes radioactive, it presents a safety issue for an uncontrolled re-entry failure especially since aerobraking places the reactor initially in a decaying Mars and Earth orbit.

Emergency Power for the Mission Module

Power technologies that were considered for emergency power are photovoltaic systems (preferably body mounted) with energy storage consisting of advanced batteries or regenerative fuel cells and fuel cells capable of using propellant grade fuel.

The emergency power system can be separate from or integrated with the main power system and could have some commonality with the Lander. Power system options are as follows:

- Body mounted photovoltaic blankets are light, simple, and rugged, but limited by available area, and, therefore, power.
- Roll-out photovoltaic blankets are compact and lightweight (possibly 25 kg for 25 kW of amorphous silicon and perhaps suitcase size), but may require EVA.
- Fuel cells are relatively lightweight, can use boiloff, excess H₂O, and any additional H₂O available in the case of an in-flight mission abort.
- Advanced rechargeable energy storage such as batteries or regenerative fuel cells must also be considered.

Mars Excursion Module (Lander)

Power requirements were estimated to be about 12 kWe for a 60-day duration. The bulk of this would be used by the ECLSS for the crew of four and the remainder used for mission operations.

The Mars Lander power requirement of 12 kWe for 60 days could be satisfied with various module sizes (1 of 12, 2 of 6 kWe, etc.) depending on requirements for redundancy and also commonality with the Mission Module.

Normal Operation

The prior discussion on normal operation for the Mission Module also holds here.

1. Photovoltaic Systems with Energy Storage

Photovoltaic blankets could be a lightweight, manually-rolled-out type designed with attachments to withstand the 300 mph dust storms. Set-up time would place demands on energy storage until the Mars terrain is prepared, the blankets are rolled out, fastened down, wired up, and operating.

Energy storage for night operation could be advanced batteries such as lithium or sodium-sulfur or regenerative fuel cells that could be integrated with the ECLSS.

This type of system could have mass of 1600 kg per 12 kWe module with some reduction of nighttime power requirements for near-term conventional technology. However, a more advanced technology, if pursued, could reduce this mass by 25 to 50 percent depending on the energy storage type.

2. Isotope/Dynamic Systems (Brayton, Rankine, or Stirling)

The prior discussion under the Mission Module also holds here. The mass could be 1500 kg per 12 kWe module--the same as the Mission Module. The isotope system is not very sensitive to dust storms, and the system power set-up time is minimal.

3. Fuel Cell System (Not Regenerative)

A hydrogen-oxygen fuel cell system has lightweight hardware--perhaps 500 kg for 12 kWe and can be integrated with the ECLSS. But here again, as with the Mission Module, the mass of fuel is prohibitive, about 7000 kg for 12 kWe for 60 days.

4. Solar Dynamic System

The prior discussion under the Mission Module also holds here. Thermal energy storage is required for night operation. The system mass is heavy--about 4000 kg for 12 kWe output which was extrapolated from Space Station studies. The system is sensitive to possible dust storms (300 mph particles) requiring some mechanism for protection. It must be carefully set up to accurately track the sun.

5. Nuclear Reactor/Power System

A nuclear reactor power system appears very applicable to the surface of Mars once a permanent base site selection is made. Requirements for multiple landings and a permanent base with propellant generation strongly favor a nuclear power system with its inherent excellent power growth capability. Reactor systems are not sensitive to nighttime or dust storms. Reactor power systems are potentially capable of operation over a wide range of power levels and can be designed at higher power than initial requirements with small mass penalties. Reactor systems can be run at lower power for early landings, then further reduced for long warm-storage periods and then ramped up to higher power to supporting increased activities for later landings and, therefore, have excellent power growth capability. This could enable a single reactor design to support a series of manned landings (and departures) at a location that could evolve into a permanent manned base. Higher power levels to support manufacturing activities and higher reliability required for permanent lunar presence would be available by deployment of additional modular reactor power systems.

Mars surface set-up time is significant, requiring a separate short duration power supply until nuclear power-up is established. The reactor must be located away from the lander at a distance dependent upon the shielding mode selected (perhaps into a hole or depression).

Due to significant heat rejection requirements, a radiator would then be deployed and power lines run back to the lander. Once the reactor starts operating, it becomes radioactive and, therefore, inaccessible. Reactor power systems are designed to operate without maintenance and, power output control functions are located in the radiation-free environment of the lander or surface base location. A 25 kWe advanced nuclear power system could be as light as 2000 kg for the Mars surface with a very minimal mass increase (perhaps 20 percent for double power) for greatly increased power capability for growth.

Emergency (or Short-Term) Power

This back-up power system can be separate from or integrated with the main power system and could have some commonality with the Mission Module. It could also be used for temporary power, as required in the case of nuclear power set-up time. Power options are as follows:

- compact, lightweight, roll-out photovoltaic blanket
- advanced rechargeable energy storage such as batteries or regenerative fuel cells
- additional H₂O for regenerative fuel cells

HYBRID ELECTRICAL POWER SYSTEM OPTION

A hybrid of several power system options was considered for the Mission Module and the Mars Excursion Module with the objective of maximizing power availability for crew safety and offering low mass and cost.

A hybrid power system could be a 12 kWe power module(s) consisting of photovoltaic, regenerative fuel cell and isotope dynamic systems optimized for mass, cost, and reliability. This combined system would yield:

- Commonality between the Mission Module and Mars Excursion Module
- Low heat rejection (over an all isotope system)
- Highest system reliability and redundancy, reducing the requirements for a separate emergency power system; enhancing crew safety
- Low power system mass (helps reduce trip time)

Photovoltaic Section

On the Mission Module, lightweight body mounted photovoltaic blankets would be resistant to forces from aerobraking and thrusting. The photovoltaic power fraction is based on available body area.

On the Mars Excursion Module, solar power could be provided by a combination of lightweight body mounted photovoltaic blankets plus roll-out blankets.

Regenerative Fuel Cell Section

On the Mission Module, the regenerative fuel cell section can use propellant boiloff and excess propellant and, in the case of a mission abort, any saved propellant.

On the Mars Excursion Module, the regenerative fuel cell section can provide sufficient instant power until the roll-out photovoltaic blanket is in place.

On both the Mission Module and Mars Excursion Module, the water electrolyzer can be integrated with the ECLSS system and the sources of electrical energy for peaking and night operation.

Isotope/Dynamic Section

On the Mission Module, an isotope/dynamic power system (IDPS) offers redundancy and a different set of failure modes than the photovoltaic and regenerative fuel cells.

On the Mars Excursion Module, the IDPS provides power until the roll-out photovoltaic blanket is in place. IDPS is relatively insensitive to night and dust storms.

On both the Mission Module and Mars Excursion Module, the isotope/dynamic power fraction is based partly on cost and isotope availability. The system startup time is minimal.

REQUIRED TECHNOLOGY DEVELOPMENT

There is considerable precursor technology development required to prepare for the Manned Mars Mission. This work must be done considerably earlier than the vehicle assembly activities that will likely be performed on the Space Station. Sufficient time must be allowed to verify new technologies and designs, incorporate improvements and thoroughly test the final versions. Some of this development work can be done on the ground. Technology development for the Mars surface would mostly be accomplished with ground testing with perhaps some very limited tests on an artificial gravity facility at low Earth orbit (LEO) to simulate the Mars gravity of 1/3 G. Significant developmental activities must be performed in the zero gravity space environment to assure proper operation and endurance. This includes development for the Mars Space Vehicle and also development for any required LEO infrastructure such as a Nuclear Water Electrolysis Propellant Depot. The planned Space Station, as currently conceived, is an excellent facility to perform the bulk of these space-based activities because of the availability of humans and considerable resources. However, safety and available space will dictate that certain activities may best be performed off the Space Station on an unmanned platform, such as developmental tests of a nuclear reactor. Some early developmental tests on the Shuttle may also be desirable.

System technology development requirements were identified without knowing which systems or combinations of systems will be selected for this mission. The actual list will be shortened by any narrowing of candidates. Each area would later be expanded into additional developmental detail of its systems, components, and materials.

Power Technology Development

Power and power-related technology development items are listed in Table 1. Activities requiring development in the space environment and involving Space Station support have been identified. It is intended that any in-space developmental tests would be accomplished with an automated system requiring minimum crew time, mostly for installation and removal.

TABLE 1

Required Technology Development of Preliminary Candidates

- Human-rated nuclear reactor with in-space technology demonstration*
- Very high capacity water electrolyzer for H-O propellant generation*
- Photovoltaic/energy storage system for mission module (Mission Module)*
- Isotope dynamic system for Mission Module and Mars surface*
- Lightweight roll-out photovoltaic/energy storage system resistant to dust storms on Mars surface
- Nuclear reactor/dynamic power system suitable for Mars surface (CO₂ atmosphere-no refractory metals)
- Fuel cell system using propellant grade H₂ and O₂*
- Lightweight body mounted photovoltaic blankets for Mission Module*
- Power system heat rejection radiator subsystem for Mars surface

* Denotes use of Space Station facilities and/or nearby infrastructure for development and technology demonstration

Suggested Technology Development Affecting Emergency Power Requirement

The following is a brief discussion of suggested technology activities for a nonpower system, the Life Support System, which is the major driver of the Mars Vehicle power system. The number one mission priority must be the safety of the crew. This reflects into a substantial emergency power requirement for up to 700 days. In the case of a failure affecting the main power system, the demands on the backup system must be reduced as much as possible to minimize the mass penalty of the backup system.

A major power consumer is the Environmental Control/Life Support System (ECLSS) required for the six crew members. This requirement is estimated to be about one half of the total requirement, which is very substantial. It is recommended that life science experiments and ECLSS research and technology be performed to minimize the power consumption

of emergency life support. This could be done in both a normal and a degraded ECLSS mode and, perhaps, a separate backup very low power consuming ECLSS system approach assuming an emergency mission abort condition, such as using part of the H-O propellant for crew oxygen and fuel cell power that outputs water for the crew.

STUDY CONCLUSIONS

The following are summarizing conclusions for this study applicable to power systems for the Mars Space Vehicle, supporting space infrastructure and the Mars surface. Technology development can be accommodated by a mix of on-the-ground and in-space activities using the Space Station and its nearby platforms.

- Space Station power technology also support propellant storage depot requirements.
- Nuclear powered propellant generation depot (water electrolysis) may offer strong benefits.
- Spinning, nonsun-pointed orbiter (for artificial G) will double solar power system mass.
- Nuclear power for the Mars surface has strong growth advantages.
- Crew survival is enhanced by a mix of power technologies and strategies.
- Advanced power technologies enable lower mission risk
 - Lower mass
 - Shorter trip time
 - Crew safety/comfort

ACKNOWLEDGEMENT

I wish to acknowledge the support of the many members of the Power Technology Division at the NASA Lewis Research Center who provided the latest information on power system state-of-the-art.

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Report Documentation Page

1. Report No. NASA TM-101436		2. Government Accession No.		3. Recipient's Catalog No.	
4. Title and Subtitle Power Considerations for an Early Manned Mars Mission Utilizing the Space Station				5. Report Date	
				6. Performing Organization Code	
7. Author(s) Martin E. Valgora				8. Performing Organization Report No. E-4472	
				10. Work Unit No. 506-49-3A	
9. Performing Organization Name and Address National Aeronautics and Space Administration Lewis Research Center Cleveland, Ohio 44135-3191				11. Contract or Grant No.	
				13. Type of Report and Period Covered Technical Memorandum	
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, D.C. 20546-0001				14. Sponsoring Agency Code	
15. Supplementary Notes Prepared for Case for Mars III cosponsored by the American Astronautical Society, Jet Propulsion Laboratory, Los Alamos National Laboratory, Ames Research Center, Lyndon B. Johnson Space Center, George C. Marshall Space Flight Center, and The Planetary Society, Boulder, Colorado, July 18-22, 1987.					
16. Abstract Power requirements and candidate electrical power sources were examined for the supporting space infrastructure for an early (2004) manned Mars mission. This two-year mission (60-day stay time) assumed a single six crew piloted vehicle with a Mars lander for four of the crew. The transportation vehicle was assumed to be a hydrogen/oxygen propulsion design with or without large aerobrakes and assembled and checked out on the LEO Space Station. The long transit time necessitated artificial gravity of the crew by rotating the crew compartments. This rotation complicates power source selection. Candidate power sources were examined for the Lander, Mars Orbiter, supporting Space Station, co-orbiting Propellant Storage Depot, and, alternatively, a co-orbiting Propellant Generation (water electrolysis) Depot. Candidates considered were photovoltaics with regenerative fuel cells or batteries, solar dynamics, isotope dynamics, and nuclear power.					
17. Key Words (Suggested by Author(s)) Power system; Mars mission; Manned mission; Propellant depot; Space Station				18. Distribution Statement Unclassified - Unlimited Subject Category 20	
19. Security Classif. (of this report) Unclassified		20. Security Classif. (of this page) Unclassified		21. No of pages 14	
				22. Price* A03	

National Aeronautics and
Space Administration

Lewis Research Center
Cleveland, Ohio 44135

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